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STRENGTH OF LAMINATED SAFETY GLASS FOR CONSTRUCTION PURPOSES

A. I. Shutov,[1] I. A. Novikov,[1] and A. N. Frank[1]

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An analytical approach to determining the impact strength of laminated glass is considered. A method is proposed for reducing material and energy consumption and the production cost of multilayer glass through the use of glasses with induced surface stresses.

Contemporary residential and office buildings are frequently equipped with laminated safety glass with various degrees of protection, whose main parameters are given in Table 1.

The testing conditions for such articles are severe enough: according to the specified standard, they ought to withstand the impact of a sphere weighting 4.11 kg (Table 2).

The purpose of the present study was to attempt an analytical description of the behavior of laminated glass under the impact of a sphere and search for possibilities of decreasing material consumption for these articles while preserving the prescribed safety properties.

A successful solution of this problem is expected to substantially lower the consumption of energy in producing laminated articles and to save expenses on the imported film used in these articles.

The proposed analytical calculation is based on an earlier developed method for the calculation of the impact strength of single-layer glass and abundant statistical data accumulated by the authors [1 – 3].

Let us consider the process of impact interaction of a body of weight m moving at a speed v_0, as it encounters a multilayer wall (Fig. 1).

It is assumed that the wall consists of n layers of a brittle material, each of them of thickness d_i and $(n - 1)$ layers of a plastic material of thickness δ_i. The brittle material is glass, and the plastic material is PVB film, which bonds together the glass panes. The impact body in this case is a sphere. The speed of interaction is

$$v_0 = \sqrt{2gH},$$

where g is the free-fall acceleration and H is the height of the sphere fall.

[1] Belgorod State Technological Academy of Construction Materials, Belgorod, Russia.

The following approach to solving the above problem is proposed: analyze the energy balance for a consecutive destruction of the layers in the laminated structure, where the initial parameter for all calculations is the kinetic energy of the sphere at the moment of its encounter with the wall:

$$E_0 = \frac{mv_0^2}{2}.$$

The destruction model has the following specifics. In the first phase of the interaction, the body makes contact with the wall, and part of the energy E_0 is transformed into potential energy with the following components:

– elastic deformation of the body $E_{\mathrm{el.b}}$;

– elastic bending of laminated glass E_{b};

TABLE 1

Degree of protection, GOST R 51136–98	Product formula*	Compliance certificate
A1	3+3++3	ROSS Ru.AYa02N07785
A2	4+4++4	ROSS Ru.AYa02N07786
A3	4+4++4++4	ROSS Ru.AYa02N07787

* Digits 3 or 4 signify the glass thickness (mm), and the symbol “+” means the presence of an adhesive polymer film, 0.38 mm thick each.

TABLE 2

Testing parameters	Degree of protection		
	A1	A2	A3
Dropping height for a sphere 100 mm in diameter and weighing 4.11 kg, m	3.5	6.5	9.5
Impact energy, J	141	262	383

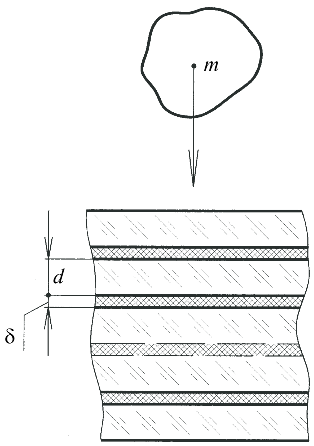

Fig. 1. Diagram of impact interaction of a body with a laminated wall.

– elastic deformation of the surface of the first glass layer $E^{(1)}_{\text{el.g}}$;

– energy of destruction of the first layer (if it happened) $E^{(1)}_{\text{f}}$.

The kinetic energy loss in the fracture of the first layer is

$$\Delta A_1 = A_{\text{el.b}} + A_{\text{b}} + E^{(1)}_{\text{el.g}} + E^{(1)}_{\text{f}}. \quad (1)$$

If the right-hand part of balance (1) is disclosed, one can find the velocity of the body after the breakthrough of the first layer:

$$v_1 = \sqrt{v_0^2 - \frac{2}{m}\Delta E_1}. \quad (2)$$

Then the body with the initial velocity v_1 interacts with the second (plastic) layer and loses part of its energy in deceleration in this layer ΔE_2. The body velocity after the breakthrough of the second layer is

$$v_2 = \sqrt{v_1^2 - \frac{2}{m}\Delta E_2}. \quad (3)$$

Next, it can be formally written:

$$\left.\begin{aligned} v_3 &= \sqrt{v_2^2 - \frac{2}{m}\Delta E_3}; \\ v_i &= \sqrt{v_{i-1}^2 - \frac{2}{m}\Delta E_i}; \\ v_n &= \sqrt{v_{n-1}^2 - \frac{2}{m}\Delta E_n}. \end{aligned}\right\} \quad (4)$$

The following particular cases may occur in consecutive computation of velocities based on formulas (2) – (4): $v_n \neq 0$ corresponds to the breakthrough of the entire laminated glass; $v_i = 0$ corresponds to the breakthrough of the first layer, whereas the $(i + 1)$th layer remains intact; $v_i = \sqrt{-B}$, the body penetrates into the ith layer to a certain depth.

Thus, the main problem of the proposed approach was to determine the energy loss ΔE_i.

Some balance (1) components were found based on the analysis of the contact interaction between a sphere and a flat surface (according to H. Hertz), which led to fairly simple relationships:

$$\left.\begin{aligned} E_{\text{el.b}} &= 2.16\frac{\sigma_{\text{el}}^2}{E_{\text{sp}}}R^3; \\ E^{(1)}_{\text{el.g}} &= 3.749\frac{\sigma_{\text{el}}^2}{E_{\text{g}}}R^2 d_1; \\ E^{(1)}_{\text{f}} &= 3.749\frac{\sigma_{\text{s}}^2}{E_{\text{g}}}R^2 d_1, \end{aligned}\right\}$$

where σ_{el} and σ_{s} are the elasticity and the strength of glass; E_{sp} and E_{g} are the Young modulus values for the sphere and the glass; R is the sphere radius.

The potential energy of elastic bending deformation was found earlier [3]:

$$E_{\text{b}} = \frac{mv^2}{2}\frac{1}{1 + \frac{1}{2}\frac{m_1}{m}},$$

where m_1 is the mass of laminated glass within the limits of the testing zones.

Consequently, all components for the first (outer) layer contacting with the sphere are determined.

The loss of energy for any ith brittle layer will only be comprised of the components $E^{(i)}_{\text{el.g}}$ and $E^{(i)}_{\text{f}}$.

The plastic layers (PVB film) behave in a different way. The energy loss in destruction of the ith plastic layer can be determined based on the energy of hydrodynamic resistance (deceleration) [4]:

$$E^{(i)}_{\text{d}} = C\rho A\,\frac{v_i^2\delta_i^2}{2},$$

where C is a constant, ρ is the density of the material, A is the cross section of the penetrating body, and δ_i is the layer thickness.

For the case of partial penetration of the sphere into a specific ith layer, the depth of the penetration into this layer was determined. For the brittle component (glass) it was equal to

$$x_i = \frac{v_{i-1}^2 m E_{\text{g}}}{14.996\sigma_{\text{s}}^2 R^2},$$

and for the plastic layer it was

$$x_i = 0.00445\,\frac{v_{i-1}^2}{v_0^2}.$$

In accordance with the above algorithm, a program for the calculation of the depth of the sphere penetration was developed.

Let us consider the breakthrough conditions for laminated glass with degree of protection A1. Setting the strength of annealed glass at the average statistical level $\sigma_{el} = \sigma_s$ = 75 MPa, the calculations predict a complete breakthrough of the laminated glass, the residual sphere velocity being equal to zero. This means that the sphere "hovers" inside the last layer, which is prescribed by the specified standard.

The earlier developed technology of thermal pulse treatment of sheet glass [4] makes it possible to "pump" surface stresses up to different levels. At the same time, in contrast to hardened glass, the destruction of this glass is not self-sustaining and occurs without fragmentation. This makes it possible to recommend the use of such glasses in multilayer structures, similar to the one considered above.

The strength of a single glass pane in this case is determined by the sum of the strength value of the annealed glass and the surface compressive stress σ_c :

$$\sigma'_s = \sigma_s + \sigma_c .$$

The calculation of the depth of the sphere penetration in accordance with the proposed method was carried out for surface tension varying from 10 to 120 MPa. (Fig. 2). It can be seen that as σ_c increases, the depth of the breakthrough of laminated glass significantly decreases. Thus, with σ_c = 80 MPa, the bottom glass layer and two PVB-film layers in the laminated structure become superfluous, while the degree of protection A1 is preserved.

Thus, the proposed approach to designing laminated safety glass for construction purposes allows for substantial savings in material and energy consumption and decreased expenses for imported film, while preserving the prescribed safety properties in the product.

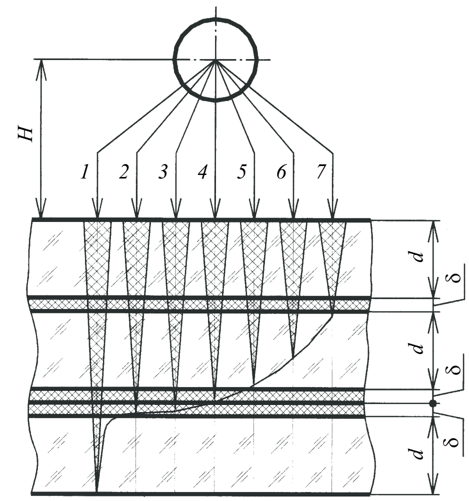

Fig. 2. The effect of the surface stress level on the breakthrough depth of the sphere: *1*, *2*, *3*, *4*, *5*, *6*, and *7*) : σ_c = 0, 20, 40, 60, 80, 100, and 120 MPa, respectively.

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